USE OF SATELLITE CLOUD PICTURES TO ESTIMATE AVERAGE RELATIVE HUMIDITY BELOW 500 MB., WITH APPLICATION TO THE GULF OF MEXICO AREA

AYLMER H. THOMPSON AND PHILIP W. WEST

Texas A&M University, College Station, Texas

ABSTRACT

This paper describes a scheme for classifying the cloudiness, as determined from satellite TV pictures, of small areas in the vicinity of radiosonde stations. The classification number, c, was correlated with the observed average relative humidity below 500 mb., $\overline{H}$, at radiosonde stations within a few hundred miles of the Gulf of Mexico and the western Caribbean Sea. For over 100 dates distributed throughout the year the relationship was found to be $\overline{H}=24.6+7.30\ c$, with a correlation coefficient of 0.78. There is a slight suggestion of seasonal and latitudinal trends. Examples show suggested average relative humidity distributions based on observations made from meteorological satellites over the waters adjacent to the southeastern United States.

1. INTRODUCTION

Present numerical forecasting techniques use estimates of information from oceanic and other areas where data are sparse or non-existent. For example, the quantitative precipitation forecast and the cloud cover forecast for the United States may utilize free-air relative humidity information not only from the land areas but from the adjacent water areas. Younkin et al. [1] have discussed a precipitation and cloud forecasting model which makes use of a vertically integrated moisture parameter, i.e., average relative humidity. There is clearly a need for more accurate estimates of such parameters over the water areas for incorporation into the numerical weather prognosis model. Charts which depict the average relative humidity and the precipitable water over the United States contain analyses which extend southward and eastward over the adjacent water areas only a few miles because, with the exception of reports from islands and a few weather ships, free-air observations have been virtually non-existent over the water areas. For this reason, the meteorologist has been forced to resort to the use of bogus data obtained by making educated guesses of the vertical structure of humidity over the oceans.

Several investigators have conducted studies correlating conventional cloud data and precipitation with the relative humidity. Smagorinsky [2] developed a linear relationship between relative humidity and cloud cover. However, Essenwanger and Haggard [3] found that cloud cover and relative humidity are related through some exponential function and the relationship is dependent upon temperature. The results of Smagorinsky can be compared only indirectly with those of Essenwanger and Haggard because Smagorinsky used space-averaged relative humidity, while Essenwanger and Haggard were dealing with point values.

Another possible source of humidity data is suggested by the availability of satellite pictures of the water areas adjacent to the United States. McClain [4] found a relation between the type of cloud conditions pictured by the satellite and the vertically integrated saturation deficit. It should be possible also to obtain a distinct relationship between the character of the cloudiness at a particular point or small area, as revealed by meteorological satellite photographs, and the average relative humidity in the column of air extending to 500 mb. above the point or small area. This paper presents a summary of efforts to determine this relationship, and to learn the means of applying the relationship to estimate the distribution of average relative humidity below 500 mb. over water areas.

2. DATA COLLECTION AND PROCESSING PROCEDURES

SELECTION OF CASES AND SOURCES OF INFORMATION

The region of the Gulf of Mexico was chosen for study because it provides a water body of moderate size encircled by many stations, particularly to the north and east, and also because of its influence on the weather situations of the eastern United States. Some 27 radiosonde stations in mainland, peninsula, and island locations provide information (usually twice daily) concerning the relative humidity distribution over and immediately adjacent to the Gulf of Mexico and the western Caribbean Sea. Specific cases were selected from those days when the TIROS satellites provided pictures of portions of the Gulf of Mexico and the adjacent land and water regions. Fairly evenly distributed by seasons, 122 orbits were selected from observations made in the years 1963 through 1965.

DATA HANDLING AND MODIFICATION PROCEDURES

The average relative humidity $\overline{H}$ of the atmospheric column below 500 mb. was computed for each station by averaging with respect to pressure. When radiosonde reports showed "motor boating" (humidity below the threshold of sensitivity of the humidity element) at some levels, the dew-point temperature was chosen as approximately two-thirds of the maximum possible dew-point temperature which could be present without being detected by the humidity element. Admittedly, the actual humidity in these cases may be far different from the assumed value, but simply to ignore these cases is to create a bias for soundings with higher relative humidities.

Most satellite pictures are taken near local noon (about 1800 GMT for the Gulf Area). The relative humidity estimates for the time of the satellite pictures were obtained by linear interpolation between radiosonde observation times (1200 GMT and 0000 GMT). This procedure is discussed also in section 4.

A numerical classification of the satellite cloud data was necessary so that a correlation with the mean relative humidity could be made, but a completely objective quantitative classification is not yet feasible. At the same time, the conventional cloud classification techniques cannot conveniently be applied to the satellite observations because in the majority of cases the individual cloud elements are too small to be resolved by the television cameras. It was decided to develop a classification system (table 1) based on the procedures employed by the National Environmental Satellite Center in preparing their routine nephanalyses. This classification considers to some degree gross vertical motion and cloud type as well as cloud amount.

Many times it is difficult using satellite TV pictures to distinguish even roughly between clouds having low tops and clouds havin quite high tops. Consequently, we used other information when necessary, in particular, the conventional cloud data observed at the several radiosonde stations and even the humidity distribution as measured by the radiosonde itself. This suggests that we might be correlating an item of data with itself, but we feel justified in using such information because satellites soon will reach a degree of sophistication that information on heights of cloud tops and moisture content for the layer above the cloud tops may be determined on a routine basis. Several writers have described these concepts; we mention only a recent paper by Rasool [5] and the discussion by Nordberg et al. [6] of the several channels of radiation information measured by satellites of the Nimbus series.

TABLE 1.—*Categories used to classify clouds observed in the satellite pictures*

Class No.	Description of Clouds
1	Clear or open to mostly open cumuliform or stratiform or cirriform with definite anticyclonic indications, or over land.
2	Mostly covered to covered thin cumuliform or stratiform or cirriform with definite anticyclonic circulation, or over land.
3	Open cumuliform with no anticyclonic indications or on south or southwest side of subtropical anticyclone—may include isolated cumulonimbus or cumulus congestus.
4	Mostly open to mostly covered cumuliform with no anticyclonic indications or on south or southwest side of subtropical anticyclone—isolated cumulonimbus or cumulus congestus may be present.
5	Mostly covered to covered stratiform without anticyclonic indications, or middle and high cloud layers.
6	Covered cumuliform with embedded cumulonimbus or cumulus congestus present.
7	Mostly covered to covered combinations of dense cumuliform, stratiform, and cirriform.
8	Clouds associated with moderate to strong frontal zone—cumulonimbus and rainshowers probable. Areas of intense, deep thunderstorms. Rain bands of hurricane.

Note: Indications of the circulation pattern may be obtained from either the composite satellite pictures or the synoptic charts or both. In most cases an analyzed surface chart is sufficient, as only the large-scale pattern is desired.

3. PRESENTATION OF RESULTS

The satellite pictures were used to classify the area around each radiosonde station pictured in each of the individual orbits chosen for study. Each classification, c, was then matched with the corresponding interpolated mean relative humidity value, $\overline{H}$, in percent. Contingency tables, correlation coefficients, and regression lines were calculated using standard statistical techniques.

Table 2 contains a representation of the frequency of the cloud classification numbers falling within various intervals of average relative humidity. The data show that for each season, as well as the entire set, the average relative humidity increases as the classification number increases. The relation appears nearly linear. The linear regression equations and correlation coefficients are given in table 3. The results are encouraging and demonstrate the usefulness of satellite data in predicting average relative humidity. The values of the correlation coefficients suggest that at least 50 percent of the variance is explained.

The several regression lines are not appreciably different, as is illustrated in figure 1. Table 4 contains a tabulation, determined from the regression lines for the seasonal and the total data, of the most likely relative humidity corresponding to each of the cloud classes. This table may be used for estimating the mean relative humidity below 500 mb. for various points on a TIROS cloud picture.

The spread of the data is indicated by the contingency tables (table 2) and by the 95-percent limits (dotted lines) of figure 1 for the total array. Some of this spread is due to the assumptions involved in the linear interpolations of the mean relative humidity. This is illustrated in the next section. Though points where linear interpolation was clearly not correct should be considered as in error, it was not considered proper to eliminate them.

The cloud classification number, c, tacitly has been assumed linear. It might be possible to improve the correlation either by assuming nonlinearity or by using a decimal classification system. Some nonlinear correlations were attempted for a small sample in preliminary investigations, but no improvement was obtained. Thus, no attempt was made to obtain nonlinear corrleations for the total array.

There is indication of a combined latitude and continental-maritime variation in the relationship between the cloud class and the average relative humidity. To check this possibility, three groups of four stations were selected, one group from Texas and Louisiana, one from northern Florida and South Carolina, and the third from Yucatan and the western Caribbean Sea. Regression lines for these three groups of stations are plotted in figure 2. It appears that there are both latitude and continentality (and perhaps even longitudinal) effects, but they are not

TABLE 2.—*Frequency of cloud classification numbers falling within the specified intervals of average relative humidity*

Average Relative Humidity	DATA FOR ALL MONTHS Cloud Class Number							
	1	2	3	4	5	6	7	8
10–19	10			1				
20–29	72	7	3		2		1	
30–39	86	35	40	21	3	3		
40–49	39	20	131	88	15	4		
50–59	11	3	87	118	57	21	3	
60–69	1		36	45	46	71	11	
70–79	1		4	15	12	57	38	1
80–89				2		21	27	4
90–100						1	4	1

Average Relative Humidity	DECEMBER TO FEBRUARY DATA Cloud Class Number							
	1	2	3	4	5	6	7	8
10–19	3							
20–29	25	3	1					
30–39	15	7	11	5	1			
40–49	4	4	36	18	10			
50–59	1		15	25	24	2	1	
60–69	1		3	6	24	12	5	
70–79	1			1	6	16	11	
80–89						6	10	
90–100						1		

Average Relative Humidity	MARCH TO MAY DATA Cloud Class Number							
	1	2	3	4	5	6	7	8
10–19	7			1				
20–29	28	3	2		2		1	
30–39	31	12	13	8	2	3		
40–49	23	8	37	28	3	2		
50–59	5	3	12	23	13	8	1	
60–69			5	6	11	21	2	
70–79			1	4	1	3	9	
80–89						2	4	
90–100							1	

Average Relative Humidity	JUNE TO AUGUST DATA Cloud Class Number							
	1	2	3	4	5	6	7	8
10–19								
20–29	2	1						
30–39	13	5	8	4				
40–49	7	3	28	21	2			
50–59	2		35	39	6	5		
60–69			16	16	4	13	2	
70–79			1	3	1	14	8	1
80–89				1		3	3	1
90–100								1

Average Relative Humidity	SEPTEMBER TO NOVEMBER DATA Cloud Class Number							
	1	2	3	4	5	6	7	8
10–19								
20–29	17							
30–39	27	11	8	4				
40–49	5	5	30	21		2		
50–59	3		25	31	14	6	1	
60–69			12	17	7	25	2	
70–79			2	7	4	24	10	
80–89				1		10	10	3
90–100							3	

great, amounting to about as much as the seasonal variation (compare figs. 1 and 2). This conclusion may not apply for a greater latitudinal or longitudinal dispersion than the 20° to 25° included in our data.

It thus appears that the relations obtained are usable relations and would provide additional information concerning the relative humidity distribution. Whether the effects of seasonal, latitudinal, and continental-maritime variations would be considered in an actual application would depend on the time available and the accuracy needed; such refinement ordinarily would be illogical in view of the spread of the data (dotted lines of fig. 1).

TABLE 3.—*Regression equations and correlation coefficients, r, relating mean relative humidity below 500 mb., $\overline{H}$, and cloudiness classification number, c*

Months	Regression Equation	Correlation Coefficient
All months	$\overline{H}=24.6+7.30\ c$	$r=0.78$
Dec.-Jan.-Feb.	$\overline{H}=20.2+8.01\ c$	$r=0.83$
Mar.-Apr.-May	$\overline{H}=22.3+7.23\ c$	$r=0.71$
June-July-Aug.	$\overline{H}=31.7+6.12\ c$	$r=0.73$
Sept.-Oct.-Nov.	$\overline{H}=28.3+6.94\ c$	$r=0.82$

TABLE 4.—*Most probable average relative humidity value, $\overline{H}$, for each classification number. Values for the entire set of data and by seasons*

All Data		Dec.-Jan.-Feb.		Mar.-Apr.-May		June-July-Aug.		Sept.-Oct.-Nov.	
Class	$\overline{H}$	Class	$\overline{H}$	Class	$\overline{H}$	Class	$\overline{H}$	Class	$\overline{H}$
1	32	1	28	1	30	1	38	1	35
2	39	2	36	2	37	2	44	2	42
3	47	3	44	3	44	3	50	3	49
4	54	4	52	4	52	4	56	4	56
5	61	5	60	5	59	5	63	5	63
6	68	6	68	6	66	6	69	6	70
7	76	7	76	7	74	7	75	7	77
8	83	8	84	8	81	8	81	8	84

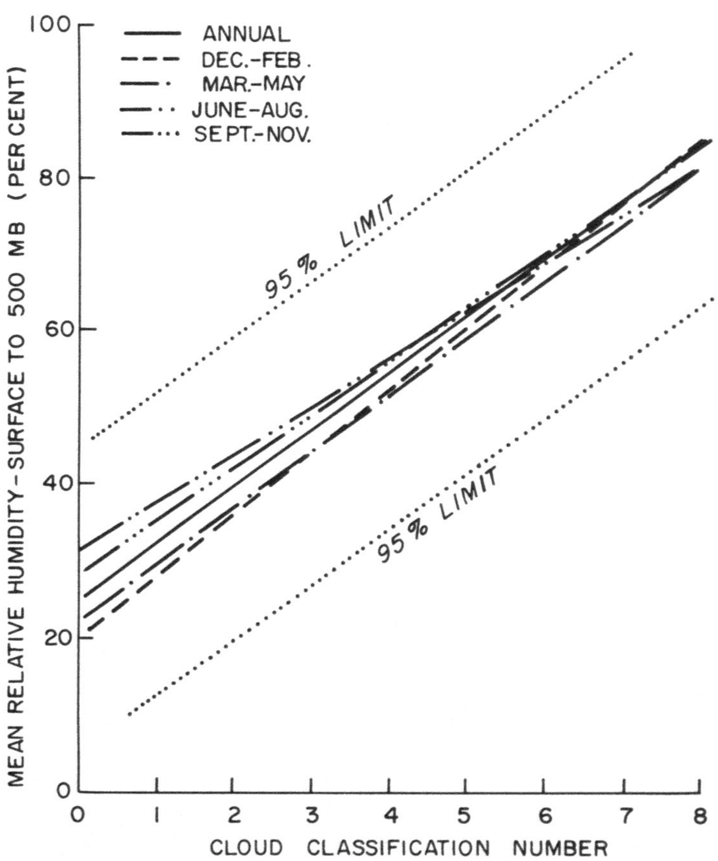

FIGURE 1.—Regression lines for the total set of data and for the several seasons.

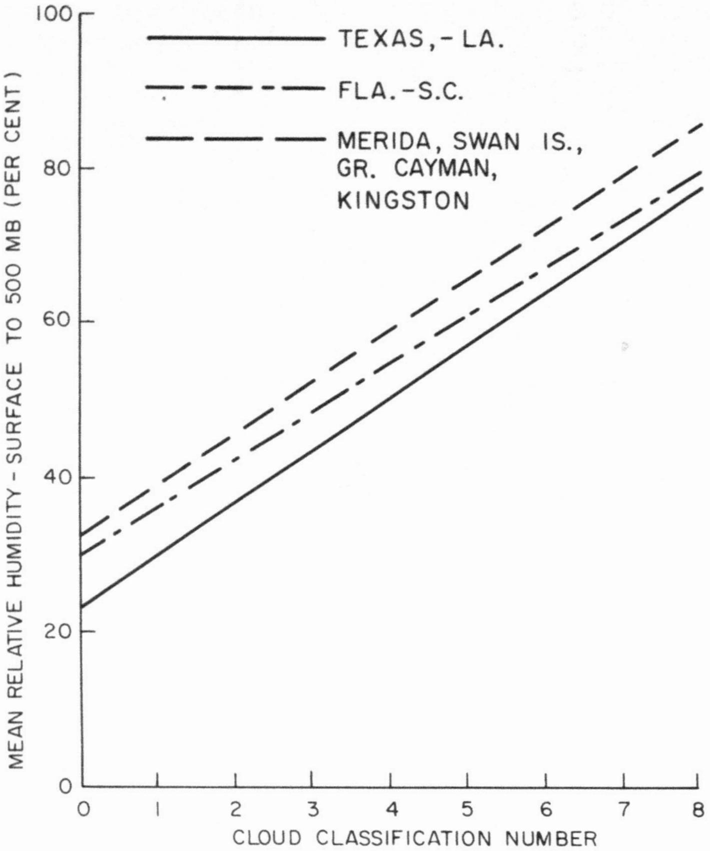

FIGURE 2.—Regression lines for selected sets of stations to show possible latitude and continentality effects.

4. ANALYSIS AND FORECAST INTERPRETATION AND APPLICATION

In this section we present two cases, one for winter and the other for summer. These cases provide examples of how the cloud systems are classified. They also show analyses of the average relative humidity pattern as determined from the clouds. These analyses may be compared with interpolated average relative humidity values obtained from radiosonde reports.

A WINTER CASE

On February 5, 1964, a surface low pressure area was centered along the Louisiana-Arkansas border. The corresponding frontal system extended southeastward into the Gulf of Mexico then southwestward to the southwest part of the Gulf. A clear area was present south of the Low and west of the front while the pre-frontal cloud and precipitation shield extended all the way to the east coast. In the southeastern part of the Gulf of Mexico and the western Caribbean Sea, several varieties of typical tropical air cloudiness were present. These features are illustrated in the nephanalysis of figure 3 and the corresponding TIROS mosaic of figure 4. Figure 3 also contains the interpolated relative humidity values (the circled figures) at the several radiosonde stations. For these same stations the cloud classification numbers as determined from the TIROS cloud pictures (the numbers in triangles) are on both figures 3 and 4. Finally, figure 3 contains a set of lines of mean relative humidity as estimated using the relationships determined in the preceding sections as applied to the TIROS cloud pictures.

It must be remembered that the classification is determined not upon conditions at the point of the station but rather upon conditions indicated by the pictures for a small area surrounding the station location. The size of this area was not fixed but in general amounted to a roughly circular area somewhat less than 100 mi. in diameter centered on the station location.

The main difficulty encountered in relating estimates of average relative humidity obtained from satellite data with those obtained from conventional radiosonde data was that the time of the radiosonde observations did not coincide with the time of the satellite picture. One way to overcome this difficulty is to obtain by interpolation the relative humidity at the time of the satellite picture. This method has some failings. At 1200 GMT on February 5, 1964, the average relative humidity at Burrwood, La., was 85 percent while 12 hr. later it had dropped to 28 percent. This gives an interpolated value at picture time of 52 percent as shown in figure 3. However, it is unlikely that the decline in the relative humidity was linear. A cold front passed Burrwood shortly after 1200 GMT and it is certain that the relative humidity dropped off sharply after that time as dry air advanced southward behind the front. At picture time Burrwood was in clear air and the cloud mass was some 100 mi. to the east. The interpolated value of 52 percent is therefore too high and a more reasonable value is 30–35 percent. The reverse would be true for a station ahead of an advancing cloud mass.

Jackson, Miss., provides a second type of interpolation problem. At the time of the TIROS picture, Jackson was in the clear air between two cloud bands. It is probable, however, that the radiosonde observations from which the interpolated value was obtained were both made in cloud bands, the earlier one in the frontal band and the later one in air which at the time of the cloud picture was over Louisiana. Thus linear interpolation resulted in the extreme discrepancy between the relative humidity estimated from the classification number and the interpolated average relative humidity.

A typical problem in drawing the average relative humidity lines occured over Alabama. In the mosaic, it will be noticed that the area in the vicinity of Montgomery appears to have thinner, less bright and more broken clouds than the areas to the northwest and to the south and east. For this reason the two 80-percent lines are drawn so they intersect the line representing the frontal band. We originally preferred to draw these two lines so they did not intersect the line indicating the frontal band, thus suggesting a continuous moist tongue from the eastern Gulf of Mexico into the northern part of Arkansas. The cloud classification for the Montgomery area indicates that our final choice (fig. 3) is a preferable analysis.

The classification indicated for Key West in figures 3 and 4 provides an example of the subjectivity of the classi-

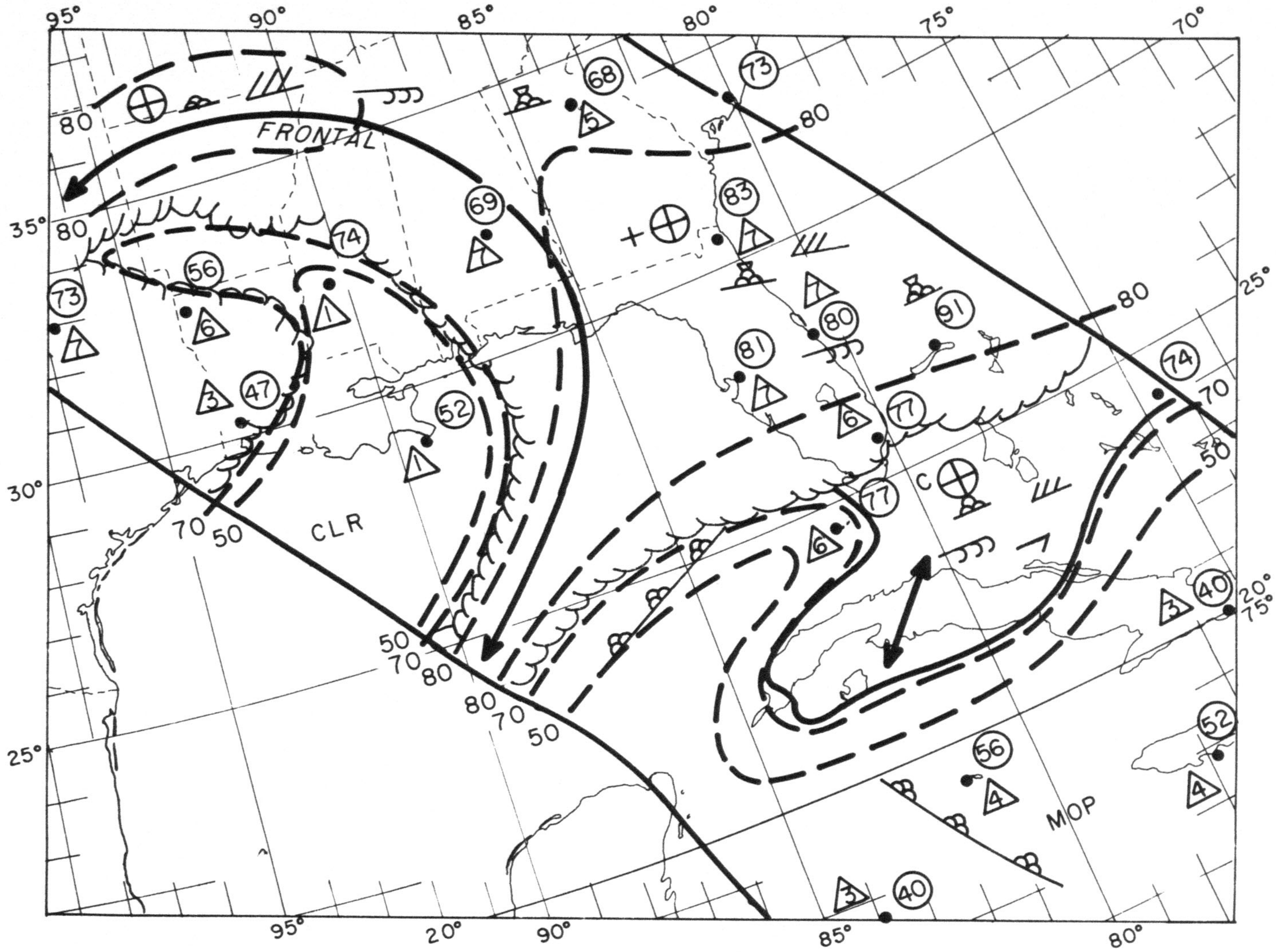

FIGURE 3.—Nephanalysis from TIROS VII cloud pictures, orbit 3421 R/O 3420, 1840 GMT, February 5, 1964. The heavy black lines indicate the boundaries of the pictures. The circled numbers are the interpolated values of the average relative humidity below 500 mb. at picture time. The dashed lines are isopleths of average relative humidity drawn for values obtained from table 4. The numbers in triangles are the classification numbers determined from the cloud pictures and table 1.

fication scheme. Of four forecasters classifying the area, two chose 6 and two chose 8 as the proper classification. The latter was chosen primarily because of the presence of small, bright cloud masses suggesting heavy shower activity near Key West (fig. 4). However, surface reports do not indicate particularly heavy activity and the area of bright clouds is not large, so the classification of 6 was selected as the best and used in the figures and in data summaries. Such use of conventional observations usually does improve the classification of a given station, and in turn improves the statistical significance of the results. However, this is consistent with the objectives of the study and with the classification scheme itself, which is not objective. Perhaps a more complex classification scheme would have prevented this difference in classification, but if much expansion is done the procedure becomes unwieldy and difficult to apply on a real-time basis. (This provides an example of nearly the maximum discrepancy obtained in our efforts; in most cases the several individuals agreed in assigning a classification to a station. In the case of Key West mentioned above, comparison of the observed average relative humidity with the data of table 3 suggests that a classification of 7 would have been best.)

In all other cases it is suggested that the classification numbers of figures 3 and 4 be checked by comparing the corresponding locations in the mosaic with the list of classifications as laid out in table 1.

A SUMMER CASE

On June 2, 1964, a quasi-stationary front extended northeast to southwest with its surface position at the southern tip of Florida hence southwest to the Yucatan Peninsula. A surface pressure ridge extended north-south across the extreme western part of the Gulf of Mexico. The main upper air trough was fairly broad and difficult to locate but was near longitude 85°W. A secondary upper air trough extended southward from the tip of Texas.

The TIROS VIII satellite took pictures of the western Gulf of Mexico shortly before noon while the TIROS VII satellite pictured the eastern Gulf and the western Caribbean Sea approximately 3 hr. later. We have com-

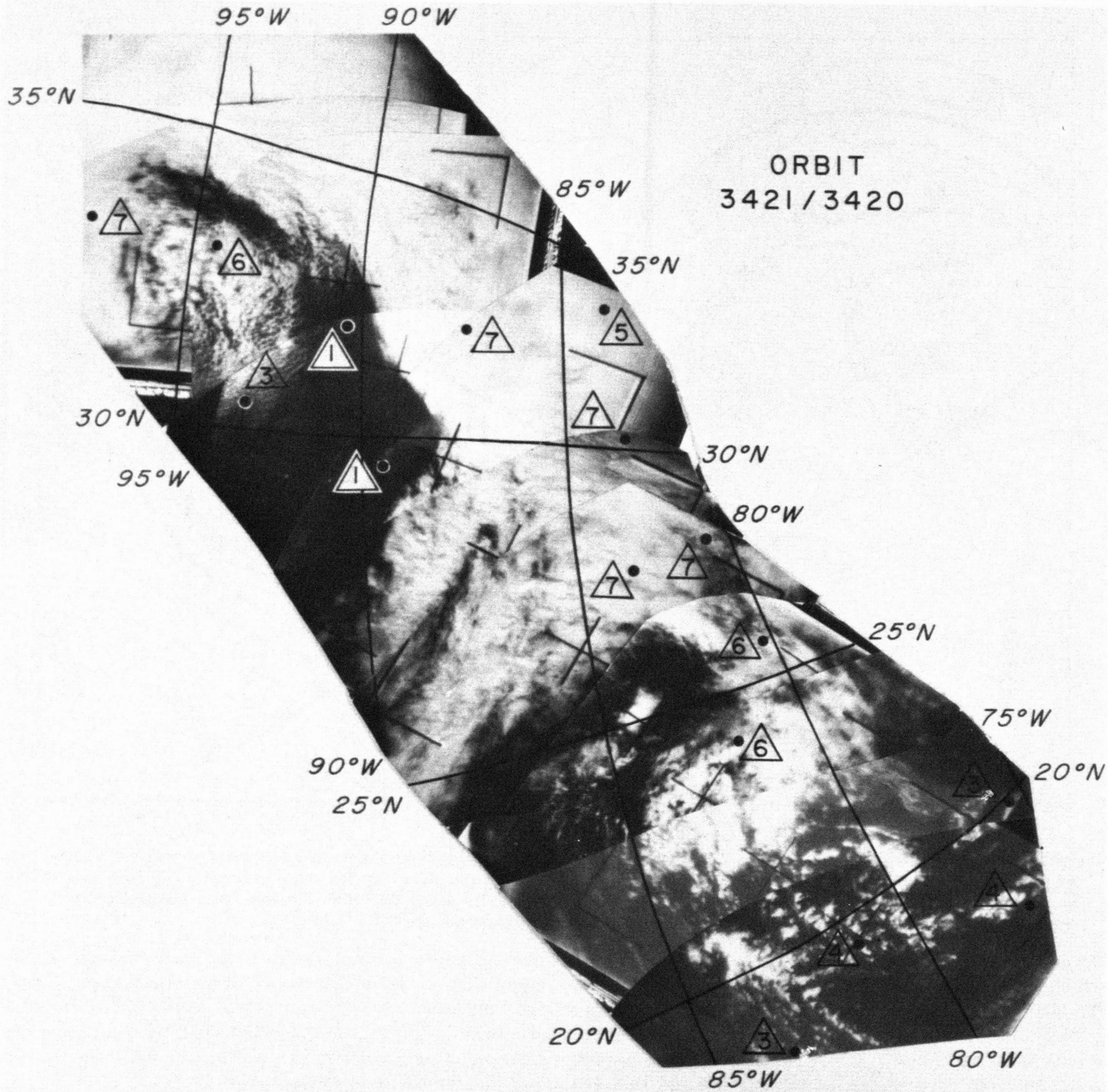

FIGURE 4.—Mosaic from TIROS VII cloud pictures, orbit 3421 R/O 3420, 1840 GMT, February 5, 1964.

bined the information from both orbits into a single nephanalysis and a single cloud mosaic, represented in figures 5 and 6, respectively. The additional information in figures 5 and 6 corresponds to that of figures 3 and 4. The region from central Texas to Alabama was included in both orbits. During the 3 hr. between orbits there was an increase in the amount of low thin clouds for most of the region of overlap, so nearly all stations during the 3-hr. period were increased from a 1 to a 2 classification; we have indicated the higher number in figures 5 and 6. An exception was Fort Worth, Texas; an altocumulus band just to the north of the station suggested a classification of 3. No interpolated average relative humidity varied by more than 5 percent; the value indicated on the map at each station is the average of the two interpolated values corresponding to the orbit times.

In the case of some of the brighter cloud masses it was sometimes difficult to know whether to apply a low number or a high number. An example is the cloud mass along the Texas-Mexico coast at about longitude 98°W. Its appearance is such that it could be either a low, dense, stratiform cloud or a high, dense, frontal band of cumulus

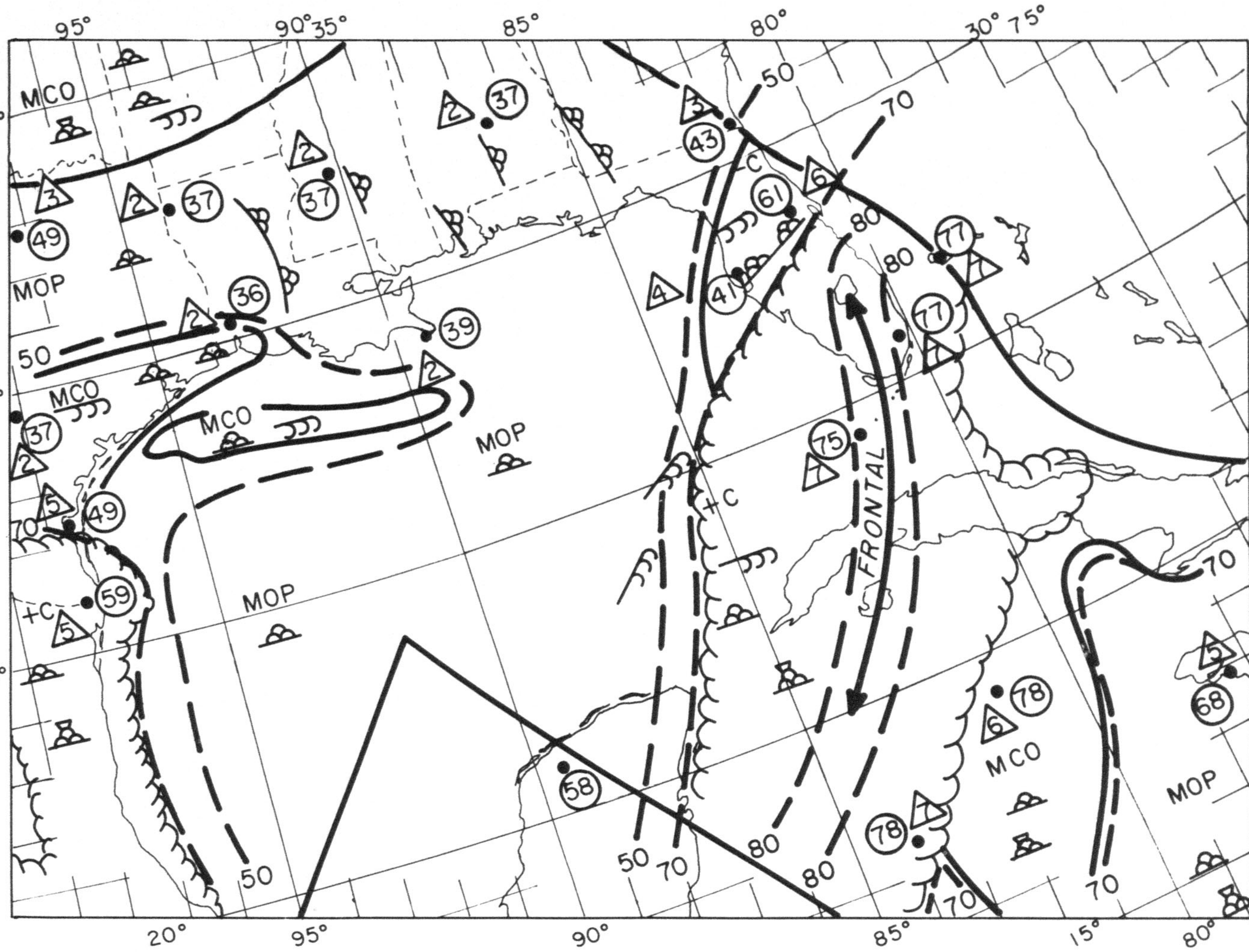

FIGURE 5.—Nephanalysis from TIROS VII cloud pictures, orbit 5167 R/O 5165, 2033 GMT, June 2, 1964, and TIROS VIII orbit 2383 R/O 2382, 1745 GMT, June 2, 1964. The heavy black lines indicate the boundaries of pictures. The circled numbers are interpolated values of the average relative humidity below 500 mb. at 1900 GMT, June 2, 1964. The dashed lines are isopleths of average relative humidity drawn for values obtained from table 4. The numbers in triangles are the classification numbers determined from the cloud pictures and table 1.

activity (compare for example with the frontal band across Florida). Radiation data, if available, would provide an indication of the cloud-top height. In this situation, we depended upon the synoptic map and the surface cloud observations. Because of the presence of cirrus clouds as well as definite thick cumulus in the southern parts of this band, we chose to apply an intermediate classification number for Brownsville and Corpus Christi, Texas, as indicated in figure 5.

Most of the other cloud classification numbers require little comment. When the classification number is compared with the corresponding area on the cloud mosaic (see also table 1), the classification numbers appear justified.

For this day, the linear interpolation method presents no apparent problems, as the frontal cloud and other cloud masses were nearly stationary. The relative humidity values appear to fit the cloud patterns well.

5. CONCLUDING REMARKS

In these cases no attempt is made to account for any possible error in the rectification of the satellite pictures. The presence of landmarks in most pictures suggested that the error was less than the usual estimate of error of two latitude degrees. In actual application, it is probably not necessary to give serious consideration to this error since the forecast implications cannot be applied that accurately.

One immediate application of the results can be seen. The average relative humidity charts prepared by the ESSA Weather Bureau can be extended through the use of the relations of section 3 to reflect the distribution of moisture over the water areas as well as the land areas. When all cloud masses have been classified on the basis of the criteria given in table 1, average relative humidity values for the various cloud formations may be obtained from the relations of section 3. Analyses should be con-

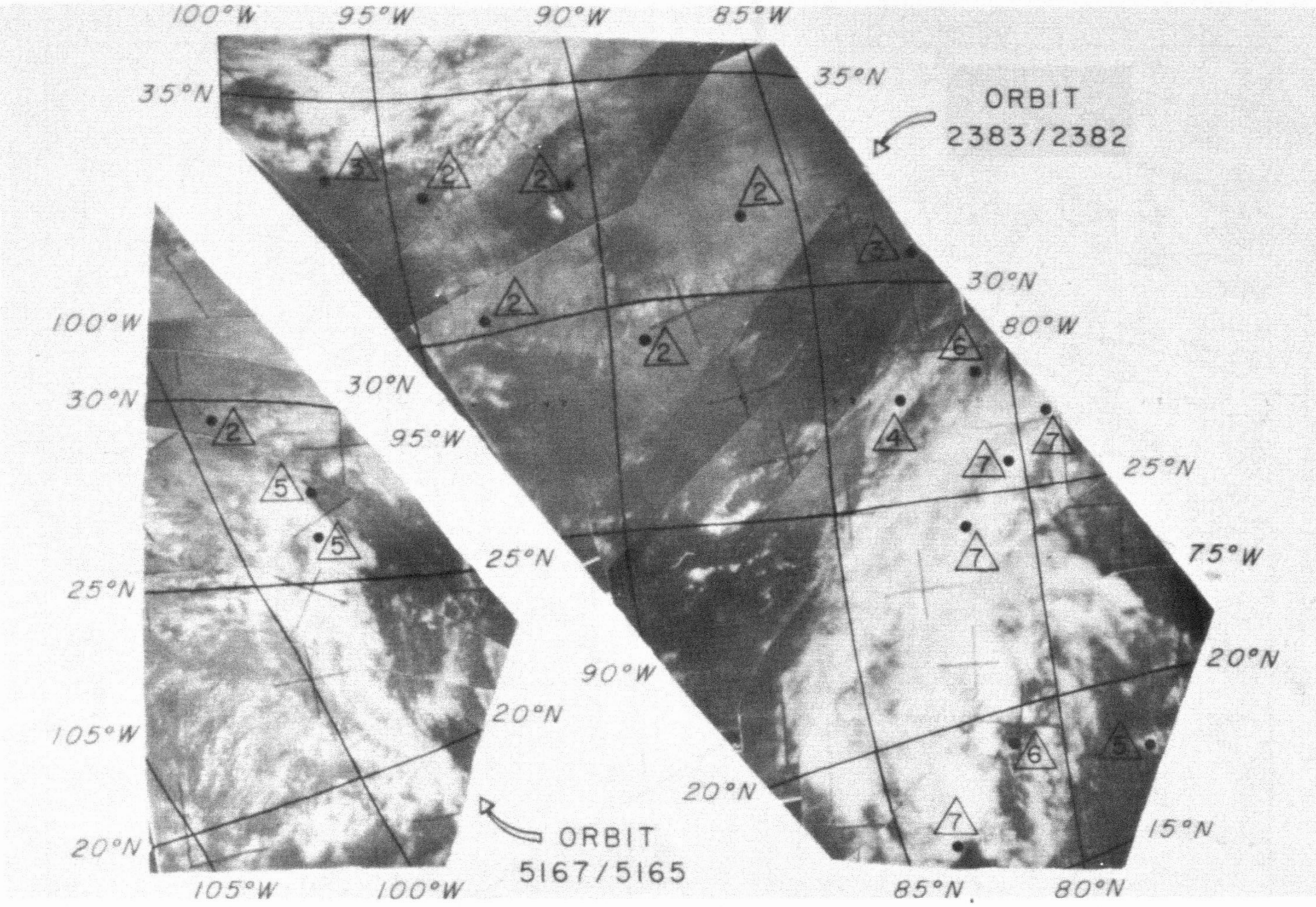

FIGURE 6.—Mosaic from TIROS VII cloud pictures, orbit 5167 R/O 5165, 2033 GMT and TIROS VIII orbit 2383 R/O 2382, 1745 GMT both on June 2, 1964.

structed such that many of the isopleths approximate the boundaries of the particular cloud masses.

The described relations should be of value and usable on a "real time" basis by experienced meteorologists after a little practice. It should be possible to draw isopleths of the moisture pattern directly on either the nephanalyses or the cloud montages, as desired. This procedure should result in a great increase in the area from which moisture estimates are available for incorporation into quantitative forecasting procedures.

The use of satellite infrared radiation data was mentioned as aiding in an improved classification of the cloud pictures. The next step in the investigations probably should be to determine procedures for use of the radiation data. The study also should be extended to other areas and carried out on a daily basis. The data from recent and planned satellites, such as the ESSA and Nimbus series, make this possible.

ACKNOWLEDGMENTS

Part of this research was sponsored by the National Environmental Satellite Center, ESSA, through Contract Cwb-11247 with the Texas A&M Research Foundation. Capt. West's contributions were made possible by the Air Force Institute of Technology which assigned him to Texas A&M University for graduate study in Meteorology. Publication does not necessarily indicate endorsement of the results by the U.S. Air Force or by ESSA.

REFERENCES

1. R. J. Younkin, J. A. LaRue, and F. Sanders, "The Objective Prediction of Clouds and Precipitation Using Vertically Integrated Moisture and Adiabatic Vertical Motions," *Journal of Applied Meteorology*, vol. 4, No. 1, Feb. 1965, pp. 3–17.
2. J. Smagorinsky, "On the Dynamical Prediction of Large-Scale Condensation by Numerical Methods," *Physics of Precipitation, Geophysical Monograph* No. 5, American Geophysical Union, Washington, D.C., 1960, pp. 71–78.
3. O. Essenwanger and G. Haggard, "The Relation Between Cloud Cover and Relative Humidity," *Final Report*, Project Order R–65–0–99856–SC–01–91, National Weather Records Center, U.S. Weather Bureau, Asheville, N.C., 1960, 73 pp.
4. E. P. McClain, "On the Relation of Satellite-Viewed Cloud Conditions to Vertically Integrated Moisture Fields," *Monthly Weather Review*, vol. 94, No. 8, Aug. 1966, pp. 509–514.
5. S. I. Rasool, "Cloud Heights and Nighttime Cloud Covers From TIROS Radiation Data," *Journal of the Atmospheric Sciences*, vol. 21, No. 2, Mar. 1964, pp. 152–156.
6. W. Nordberg, A. W. McCulloch, L. L. Foshee, and W. R. Bandeen, "Preliminary Results from Nimbus II," *Bulletin of the American Meteorological Society*, vol. 47, No. 11, Nov. 1966, pp. 857–872.

[Received February 16, 1967; revised August 3, 1967]